The Basic Idea

Texture mapping is a computer graphics operation in which a separate image, referred to as the texture, is stretched onto a piece of 3D geometry and follows it however it is transformed. This image is also known as a texture map.

Also, to prevent confusion, the texture pixels are not called pixels. A pixel is a dot in the final screen image. A dot in the texture image is called a texture element, or texel.

Similarly, to avoid terminology confusion, a texture’s width and height dimensions are not called X and Y. They are called S and T. A texture map is not generally indexed by its actual resolution coordinates. Instead, it is indexed by a coordinate system that is resolution-independent. The left side is always S=0, the right side is S=1, the bottom is T=0, and the top is T=1. Thus, you do not need to be aware of the texture’s resolution when you are specifying coordinates that point into it. Think of S and T as a measure of what fraction of the way you are into the texture.
The Basic Idea

The mapping between the geometry of the 3D object and the S and T of the texture image works like this:

\[(X0, Y0, S0, T0)\]
\[(X1, Y1, S1, T1)\]
\[(X2, Y2, S2, T2)\]
\[(X3, Y3, S3, T3)\]
\[(X4, Y4, S4, T4)\]

Interpolated \((S,T) = (0.78, 0.67)\) in S and T = (199.68, 171.52) in texels

You specify an \((s,t)\) pair at each vertex, along with the vertex coordinate. At the same time that the rasterizer is interpolating the coordinates, colors, etc. inside the polygon, it is also interpolating the \((s,t)\) coordinates. Then, when it goes to draw each pixel, it uses that pixel's interpolated \((s,t)\) to lookup a color in the texture image.

Enable texture mapping:

```
glEnable( GL_TEXTURE_2D );
```

Draw your polygons, specifying \(s\) and \(t\) at each vertex:

```
glBegin( GL_POLYGON );
glTexCoord2f( s0, t0 );
glNormal3f( nx0, ny0, nz0 );
glVertex3f( x0, y0, z0 );
glTexCoord2f( s1, t1 );
glNormal3f( nx1, ny1, nz1 );
glVertex3f( x1, y1, z1 );
```

```
...
```

```
glEnd( );
```

Disable texture mapping:

```
glDisable( GL_TEXTURE_2D );
```
Triangles in an Array of Structures

```
struct vertex
{
    glm::vec3 position;
    glm::vec3 normal;
    glm::vec3 color;
    glm::vec2 texCoord;
};

struct vertex VertexData[] =
{
    // triangle 0-2-3:
    // vertex #0:
    { -1., -1., -1. },
    {  0.,  0., -1. },
    {  0.,  0.,  0. },
    {  1., 0. },
    // vertex #2:
    { -1.,  1., -1. },
    {  0.,  0., -1. },
    {  0.,  1.,  0. },
    {  1., 1. },
    // vertex #3:
    {  1.,  1., -1. },
    {  0.,  0., -1. },
    {  1.,  1.,  0. },
    {  0., 1. }
};
```

Using a Texture: How do you know what (s,t) to assign to each vertex?

The easiest way to figure out what s and t are at a particular vertex is to figure out what fraction across the object the vertex is living at. For a plane,

\[
s = \frac{x - X_{\text{min}}}{X_{\text{max}} - X_{\text{min}}}
\]

\[
t = \frac{y - Y_{\text{min}}}{Y_{\text{max}} - Y_{\text{min}}}
\]
Using a Texture: How do you know what \((s,t)\) to assign to each vertex?

Or, for a sphere,

\[ s = \frac{\Theta - (-\pi)}{2\pi}, \quad t = \frac{\Phi - (-\pi/2)}{\pi} \]

\[ s = (\text{lng} + \text{M}\_\text{PI}) / (2.*\text{M}\_\text{PI}); \]
\[ t = (\text{lat} + \text{M}\_\text{PI}/2.) / \text{M}\_\text{PI}; \]

Using a Texture: How do you know what \((s,t)\) to assign to each vertex?

Uh-oh. Now what? Here’s where it gets tougher…,
You really are at the mercy of whoever did the modeling...

Be careful where $s$ abruptly transitions from 1. back to 0.
Memory Types

NVIDIA Discrete Graphics:
- 11 Memory Types:
  - Memory 0:
  - Memory 1:
  - Memory 2:
  - Memory 3:
  - Memory 4:
  - Memory 5:
  - Memory 6:
  - Memory 7: DeviceLocal
  - Memory 8: DeviceLocal
  - Memory 9: HostVisible HostCoherent
  - Memory 10: HostVisible HostCoherent HostCached

Intel Integrated Graphics:
- 3 Memory Types:
  - Memory 0: DeviceLocal
  - Memory 1: DeviceLocal HostVisible HostCoherent
  - Memory 2: DeviceLocal HostVisible HostCoherent HostCached
Texture Sampling Parameters

```c
glfwTerminate();
glTexParameteri( GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_REPEAT );
glTexParameteri( GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_REPEAT );
glTexParameteri( GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, GL_LINEAR );
glTexParameteri( GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_LINEAR );
```

```c
VkSamplerCreateInfo vsci;

vsci.magFilter = VK_FILTER_LINEAR;
vsci.minFilter = VK_FILTER_LINEAR;
vsci.mipmapMode = VK_SAMPLER_MIPMAP_MODE_LINEAR;
vsci.addressModeU = VK_SAMPLER_ADDRESS_MODE_REPEAT;
vsci.addressModeV = VK_SAMPLER_ADDRESS_MODE_REPEAT;
vsci.addressModeW = VK_SAMPLER_ADDRESS_MODE_REPEAT;

result = vkCreateSampler( LogicalDevice, IN &vsci, PALLOCATOR, pTextureSampler );
```

Textures' Undersampling Artifacts

As an object gets farther away and covers a smaller and smaller part of the screen, the texels : pixels ratio used in the coverage becomes larger and larger. This means that there are pieces of the texture leftover in between the pixels that are being drawn into, so that some of the texture image is not being taken into account in the final image. This means that the texture is being undersampled and could end up producing artifacts in the rendered image.

Consider a texture that consists of one red texel and all the rest white. It is easy to imagine an object rendered with that texture as ending up all white, with the red texel having never been included in the final image. The solution is to create lower-resolution textures of the same texture so that the red texel gets included somehow in all resolution-level textures.
Texture Mipmap-mapping

- Total texture storage is ~ 2x what it was without mipmap-mapping
- Graphics hardware determines which level to use based on the texels : pixels ratio.
- In addition to just picking one mipmap level, the rendering system can sample from two of them, one less that the T:P ratio and one more, and then blend the two RGBAs returned. This is known as VK_SAMPLER_MIPMAP_MODE_LINEAR.

\[\text{Average 4 pixels to make a new one}\]

* Latin: *multim in parvo*, "many things in a small place"

```cpp
VkResult Init07TextureSampler(MyTexture *pMyTexture)
{
    VkResult result;
    VkSamplerCreateInfo vsci;
    vsci.sType = VK_STRUCTURE_TYPE_SAMPLER_CREATE_INFO;
    vsci.pNext = nullptr;
    vsci.flags = 0;
    vsci.magFilter = VK_FILTER_LINEAR;
    vsci.minFilter = VK_FILTER_LINEAR;
    vsci.mipmapMode = VK_SAMPLER_MIPMAP_MODE_LINEAR;
    vsci.addressModeU = VK_SAMPLER_ADDRESS_MODE_REPEAT;
    vsci.addressModeV = VK_SAMPLER_ADDRESS_MODE_REPEAT;
    vsci.addressModeW = VK_SAMPLER_ADDRESS_MODE_REPEAT;
    #ifdef CHOICES
    VK_SAMPLER_ADDRESS_MODE_REPEAT
    VK_SAMPLER_ADDRESS_MODE_MIRRORED_REPEAT
    VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_EDGE
    VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_BORDER
    VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE
    #endif
    vsci.mipLodBias = 0.;
    vsci.anisotropyEnable = VK_FALSE;
    vsci.maxAnisotropy = 1.;
    vsci.compareEnable = VK_FALSE;
    vsci.compareOp = VK_COMPARE_OP_NEVER;
    #ifdef CHOICES
    VK_COMPARE_OP_NEVER
    VK_COMPARE_OP_LESS
    VK_COMPARE_OP_EQUAL
    VK_COMPARE_OP_LESS_OR_EQUAL
    VK_COMPARE_OP_GREATER
    VK_COMPARE_OP_NOT_EQUAL
    VK_COMPARE_OP_GREATER_OR_EQUAL
    VK_COMPARE_OP_ALWAYS
    #endif
    vsci.minLod = 0.;
    vsci.maxLod = 0.;
    vsci.borderColor = VK_BORDER_COLOR_FLOAT_OPAQUE_BLACK;
    #ifdef CHOICES
    VK_BORDER_COLOR_FLOAT_TRANSPARENT_BLACK
    VK_BORDER_COLOR_INT_TRANSPARENT_BLACK
    VK_BORDER_COLOR_FLOAT_OPAQUE_BLACK
    VK_BORDER_COLOR_INT_OPAQUE_BLACK
    VK_BORDER_COLOR_FLOAT_OPAQUE_WHITE
    VK_BORDER_COLOR_INT_OPAQUE_WHITE
    #endif
    vsci.unnormalizedCoordinates = VK_FALSE;

    result = vkCreateSampler(LogicalDevice, IN &vsci, PALLOCATOR, OUT &pMyTexture->texSampler);
}
```
VkResult
InitTextureBuffer(INOUT MyTexture * pMyTexture)
{

VkResult result;
uint32_t texWidth = pMyTexture->width;
uint32_t texHeight = pMyTexture->height;
unsigned char *texture = pMyTexture->pixels;
VkDeviceSize textureSize = texWidth * texHeight * 4;            // rgba, 1 byte each

VkImage stagingImage;
VkImage textureImage;

// this first {...} is to create the staging image:
{
  VkImageCreateInfo vici;
  vici.sType = VK_STRUCTURE_TYPE_IMAGE_CREATE_INFO;
  vici.pNext = nullptr;
  vici.flags = 0;
  vici.imageType = VK_IMAGE_TYPE_2D;
  vici.format = VK_FORMAT_R8G8B8A8_UNORM;
  vici.extent.width = texWidth;
  vici.extent.height = texHeight;
  vici.extent.depth = 1;
  vici.mipLevels = 1;
  vici.arrayLayers = 1;
  vici.samples = VK_SAMPLE_COUNT_1_BIT;
  vici.tiling = VK_IMAGE_TILING_LINEAR;
  #ifdef CHOICES
  vici.usage = VK_IMAGE_USAGE_TRANSFER_SRC_BIT;
  #endif
  #ifdef CHOICES
  vici.tiling = VK_IMAGE_TILING_LINEAR;
  #endif
  vici.sharingMode = VK_SHARING_MODE_EXCLUSIVE;
  #ifdef CHOICES
  vici.queueFamilyIndexCount = 0;
  vici.pQueueFamilyIndices = (const uint32_t *)nullptr;
  result = vkCreateImage(LogicalDevice, IN &vici, PALLOCATOR, OUT &stagingImage); // allocated, but not filled
  VkMemoryRequirements vmr;
  vkGetImageMemoryRequirements(LogicalDevice, IN stagingImage, OUT &vmr);
  if (Verbose)
  {
    fprintf(FpDebug, "Image vmr.size = %lld
", vmr.size);
    fprintf(FpDebug, "Image vmr.alignment = %lld
", vmr.alignment);
    fprintf(FpDebug, "Image vmr.memoryTypeBits = 0x%08x
", vmr.memoryTypeBits);
    fflush(FpDebug);
  }
  VkMemoryAllocateInfo vmai;
  vmai.sType = VK_STRUCTURE_TYPE_MEMORY_ALLOCATE_INFO;
  vmai.pNext = nullptr;
  vmai.allocationSize = vmr.size;
  vmai.memoryTypeIndex = FindMemoryThatIsHostVisible();   // because we want to mmap it
  VkDeviceMemory vdm;
  result = vkAllocateMemory(LogicalDevice, IN &vmai, PALLOCATOR, OUT &vdm);
  pMyTexture->vdm = vdm;
  result = vkBindImageMemory(LogicalDevice, IN stagingImage, IN vdm, 0);  // 0 = offset
  // we have now created the staging image -- fill it with the pixel data:
  VkImageSubresource vis;
  vis.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT;
  vis.mipLevel = 0;
  vis.arrayLayer = 0;

  VkSubresourceLayout vsl;
  vkGetImageSubresourceLayout(LogicalDevice, stagingImage, IN &vis, OUT &vsl);
  if (Verbose)
  {
    
  }
}
```c
void *gpuMemory;

vkMapMemory(LogicalDevice, vdm, 0, VK_WHOLE_SIZE, 0, OUT &gpuMemory);
// 0 and 0 = offset and memory map flags
if (vsl.rowPitch == 4 * texWidth)
{
    memcpy(gpuMemory, (void *)texture, (size_t)textureSize);
}
else
{
    unsigned char *gpuBytes = (unsigned char *)gpuMemory;
    for (unsigned int y = 0; y < texHeight; y++)
    {
        memcpy(&gpuBytes[y * vsl.rowPitch], &texture[4 * y * texWidth], (size_t)(4*texWidth) );
    }
}

vkUnmapMemory(LogicalDevice, vdm);

// ******************************************************************************
// this second {...} is to create the actual texture image:
// ******************************************************************************
{
    VkImageCreateInfo vici;
    vici.sType = VK_STRUCTURE_TYPE_IMAGE_CREATE_INFO;
    vici.pNext = nullptr;
    vici.flags = 0;
    vici.imageType = VK_IMAGE_TYPE_2D;
    vici.format = VK_FORMAT_R8G8B8A8_UNORM;
    vici.extent.width = texWidth;
    vici.extent.height = texHeight;
    vici.extent.depth = 1;
    vici.mipLevels = 1;
    vici.arrayLayers = 1;
    vici.samples = VK_SAMPLE_COUNT_1_BIT;
    vici.tiling = VK_IMAGE_TILING_OPTIMAL;
    vici.usage = VK_IMAGE_USAGE_TRANSFER_DST_BIT | VK_IMAGE_USAGE_SAMPLED_BIT;  // because we are transferring into it and will eventual sample from it
    vici.sharingMode = VK_SHARING_MODE_EXCLUSIVE;
    vici.queueFamilyIndexCount = 0;
    vici.pQueueFamilyIndices = (const uint32_t *)nullptr;
    result = vkCreateImage(LogicalDevice, IN &vici, PALLOCATOR, OUT &textureImage); // allocated, but not filled
    VkMemoryRequirements vmr;
    vkGetImageMemoryRequirements(LogicalDevice, IN textureImage, OUT &vmr);
    if( Verbose )
    {
        fprintf(FpDebug, "Texture vmr.size = %lld
", vmr.size);
        fprintf(FpDebug, "Texture vmr.alignment = %lld
", vmr.alignment);
        fprintf(FpDebug, "Texture vmr.memoryTypeBits = 0x%08x
", vmr.memoryTypeBits);
        fflush(FpDebug);
    }
    VkMemoryAllocateInfo vmai;
    vmai.sType = VK_STRUCTURE_TYPE_MEMORY_ALLOCATE_INFO;
    vmai.pNext = nullptr;
    vmai.allocationSize = vmr.size;
    vmai.memoryTypeIndex = FindMemoryThatIsDeviceLocal();  // because we want to sample from it
    VkDeviceMemory vdm;
    result = vkAllocateMemory(LogicalDevice, IN &vmai, PALLOCATOR, OUT &vdm);
    result = vkBindImageMemory(LogicalDevice, IN textureImage, IN vdm, 0);  // 0 = offset
}
```

// copy pixels from the staging image to the texture:
VKCommandBufferBeginInfo vbcbi;
vcbi.sType = VK_STRUCTURE_TYPE_COMMAND_BUFFER_BEGIN_INFO;
vcbi.pNext = nullptr;
vcbi.flags = VK_COMMAND_BUFFER_USAGE_ONE_TIME_SUBMIT_BIT;
vcbi.pInheritanceInfo = (VkCommandBufferInheritanceInfo *)nullptr;
result = vkBeginCommandBuffer( TextureCommandBuffer, IN &vbcbi);

// ******************************************************************************
// transition the staging buffer layout:
// ******************************************************************************
{
VkImageSubresourceRange visr;
visr.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT;
visr.baseMipLevel = 0;
visr.levelCount = 1;
visr.baseArrayLayer = 0;
visr.layerCount = 1;

VkImageMemoryBarrier vimb;
vimb.sType = VK_STRUCTURE_TYPE_IMAGE_MEMORY_BARRIER;
vimb.pNext = nullptr;
vimb.oldLayout = VK_IMAGE_LAYOUT_PREINITIALIZED;
vimb.newLayout = VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL;
vimb.srcQueueFamilyIndex = VK_QUEUE_FAMILY_IGNORED;
vimb.dstQueueFamilyIndex = VK_QUEUE_FAMILY_IGNORED;
vimb.image = stagingImage;
vimb.srcAccessMask = VK_ACCESS_HOST_WRITE_BIT;
vimb.dstAccessMask = 0;
vimb.subresourceRange = visr;
vCmdPipelineBarrier( TextureCommandBuffer,
VK_PIPELINE_STAGE_HOST_BIT, VK_PIPELINE_STAGE_HOST_BIT, 0,
0, (VkMemoryBarrier *)nullptr,
0, (VkBufferMemoryBarrier *)nullptr,
1, IN &vimb);
}

// ******************************************************************************
// transition the texture buffer layout:
// ******************************************************************************
{
VkImageSubresourceRange visr;
visr.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT;
visr.baseMipLevel = 0;
visr.levelCount = 1;
visr.baseArrayLayer = 0;
visr.layerCount = 1;

VkImageMemoryBarrier vimb;
vimb.sType = VK_STRUCTURE_TYPE_IMAGE_MEMORY_BARRIER;
vimb.pNext = nullptr;
vimb.oldLayout = VK_IMAGE_LAYOUT_PREINITIALIZED;
vimb.newLayout = VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL;
vimb.srcQueueFamilyIndex = VK_QUEUE_FAMILY_IGNORED;
vimb.dstQueueFamilyIndex = VK_QUEUE_FAMILY_IGNORED;
vimb.image = textureImage;
vimb.srcAccessMask = 0;
vimb.dstAccessMask = VK_ACCESS_TRANSFER_WRITE_BIT;
vimb.subresourceRange = visr;
}

vkCmdPipelineBarrier( TextureCommandBuffer,
VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT, VK_PIPELINE_STAGE_TRANSFER_BIT, 0,
0, (VkMemoryBarrier *)nullptr,
0, (VkBufferMemoryBarrier *)nullptr,
1, IN &vimb);
VkImageCopy vic;
  vic.srcSubresource = visl;
  vic.srcOffset = vo3;
  vic.dstSubresource = visl;
  vic.dstOffset = vo3;
  vic.extent = ve3;

vkCmdCopyImage(TextureCommandBuffer, stagingImage, VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL, textureImage, VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL, 1, IN &vic);

// *******************************************************************************
// transition the texture buffer layout a second time:
// *******************************************************************************
{
    VkImageSubresourceRange visr;
    visr.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT;
    visr.baseMipLevel = 0;
    visr.levelCount = 1;
    visr.baseArrayLayer = 0;
    visr.layerCount = 1;

    VkImageMemoryBarrier vimb;
    vimb.sType = VK_STRUCTURE_TYPE_IMAGE_MEMORY_BARRIER;
    vimb.pNext = nullptr;
    vimb.oldLayout = VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL;
    vimb.newLayout = VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL;
    vimb.srcQueueFamilyIndex = VK_QUEUE_FAMILY_IGNORED;
    vimb.dstQueueFamilyIndex = VK_QUEUE_FAMILY_IGNORED;
    vimb.image = textureImage;
    vimb.srcAccessMask = 0;
    vimb.dstAccessMask = VK_ACCESS_SHADER_READ_BIT;
    vimb.subresourceRange = visr;

    vkCmdPipelineBarrier(TextureCommandBuffer, VK_PIPELINE_STAGE_TRANSFER_BIT, VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT, 0, 0, (VkMemoryBarrier *)nullptr, 0, (VkBufferMemoryBarrier *)nullptr, 1, IN &vimb);
    // *******************************************************************************
    result = vkEndCommandBuffer(TextureCommandBuffer);

    VkSubmitInfo vsi;
    vsi.sType = VK_STRUCTURE_TYPE_SUBMIT_INFO;
    vsi.pNext = nullptr;
    vsi.commandBufferCount = 1;
    vsi.pCommandBuffers = &TextureCommandBuffer;
    vsi.waitSemaphoreCount = 0;
    vsi.pWaitSemaphores = (VkSemaphore *)nullptr;
    vsi.signalSemaphoreCount = 0;
    vsi.pSignalSemaphores = (VkSemaphore *)nullptr;
    vsi.pWaitDstStageMask = (VkPipelineStageFlags *)nullptr;
    result = vkQueueSubmit(Queue, 1, IN &vsi, VK_NULL_HANDLE);

    result = vkQueueWaitIdle(Queue);
}
// create an image view for the texture image:
// (an "image view" is used to indirectly access an image)
VkImageSubresourceRange visr;
visr.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT;
visr.baseMipLevel = 0;
visr.levelCount = 1;
visr.baseArrayLayer = 0;
visr.layerCount = 1;

VkImageViewCreateInfo vivci;
vivci.sType = VK_STRUCTURE_TYPE_IMAGE_VIEW_CREATE_INFO;
vivci.pNext = nullptr;
vivci.flags = 0;
vivci.image = textureImage;
vivci.viewType = VK_IMAGE_VIEW_TYPE_2D;
vivci.format = VK_FORMAT_R8G8B8A8_UNORM;
vivci.components.r = VK_COMPONENT_SWIZZLE_R;
vivci.components.g = VK_COMPONENT_SWIZZLE_G;
vivci.components.b = VK_COMPONENT_SWIZZLE_B;
vivci.components.a = VK_COMPONENT_SWIZZLE_A;
vivci.subresourceRange = visr;
result = vkCreateImageView(LogicalDevice, IN &vivci, PALLOCATOR, OUT &pMyTexture->texImageView);
return result;

Note that, at this point, the Staging Buffer is no longer needed, and can be destroyed.

Reading in a Texture from a BMP File

typedef struct MyTexture
{
    uint32_t width;
    uint32_t height;
    VkImage texImage;
    VkImageView texImageView;
    VkSampler texSampler;
    VkDeviceMemory vdm;
} MyTexture;

MyTexture MyPuppyTexture;

result = Init06TextureBufferAndFillFromBmpFile ("puppy.bmp", &MyTexturePuppy);
Init06TextureSampler( &MyPuppyTexture.texSampler );

This function can be found in the sample.cpp file. The BMP file needs to be created by something that writes uncompressed 24-bit color BMP files, or was converted to the uncompressed BMP format by a tool such as ImageMagick's convert, Adobe Photoshop, or GNU's GIMP.